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AD-A230 389

FY90 End of Fiscal Year Letter
(01 Oct 1989 - 30 Sep 1990)

ONR CONTRACT INFORMATION

Contract Title: Novel High Speed Devices and Heterostructures Prepared by Molecular Beam Epitaxy

Performing Organization: University of Illinois, Urbana/Champaign

Principal Investigator: H. Morkoc

Contract Number: N00014-86-k-0513

R & T Project Number: S400005SRQ05

ONR Scientific Officer: M. Yoder

Enclosure (1)

A. Description of scientific research goals

The research grant # N00014-86-K-0513 is funding the following projects - Metal–Insulator–Semiconductor Field–Effect–Transistor (MISFET), Ge/GaAs Heterojunction Bipolar Transistor (HBT), power HBT, and a theoretical investigation on Direct and Resonant Tunneling Diode (RTD). Research goals for these projects are described separately below.

Research goals for the MISFET project

High speed transistors, e.g., Modulation–doped Field–Effect transistors and Heterojunction Bipolar transistors, based on compound semiconductors are well–known. In this project we investigate the properties of MISFET type structures based on compound semiconductors. MISFET's have advantages over the aforementioned transistors in areas where high speed, simplicity of fabrication, uniformity of threshold voltages, low standby power, and high gate operational voltages are required. To obtain an operational MISFET, it is important that the insulator and semiconductor interface be relatively defect free, the minimum requirement being that the surface Fermi level must not be pinned. Therefore, the first part of this project involves the understanding of the surface Fermi level pinning effect in compound semiconductors. The investigation will also involve the use of Ge and Si cap layers to prevent the surface Fermi level from pinning in compound semiconductors. With an unpinned surface, the next stage of the project is to obtain a MISFET on compound semiconductors.

Apart from an unpinned surface, the performance of a MISFET is highly dependent on the bulk quality of the gate dielectirc. For example, low leakage current through the gate dielectric is highly desirable for low standby power and high gate operational voltages applications. We have set–up a remote plasma chemical vapor deposition chamber which allows us to deposit ex–situ high quality SiO_2. One part of this project is the investigation of the quality of the deposited SiO_2 using a rf plasma source. Both I–V and C–V measurements are used to characterize both the bulk and interface qualities of the SiO_2.

Research goals for the Ge/GaAs HBT project

Our major research goal is to investigate Ge/GaAs heterojunctions towards incorporating Ge in well established GaAs Heterojunction Bipolar Transistors (HBT's). This novel material combination will result in enhanced device performance. For HBT's, critical parameters affecting the device performance are base doping, base contact resistance, and band discontinuities at the emitter base junction. The semiconductor Ge has excellent potential to improve the performance of GaAs/AlGaAs HBT's. Ge has a higher hole mobility and can be doped higher than any other device grade semiconductor. Heavily doped Ge can be used as low resistance base in n-p-n HBT's. Higher injection efficiencies and lower contact resistance can be achieved since Ge has a smaller band gap compared to GaAs. Due to the small recombination velocity of Ge, the dependence of current gain on the device size can also be eliminated. Apart from the HBT as a device, the growth of GaAs/Ge and Ge/GaAs heterojunctions is also investigated in detail.

Research goals for the Power HBT project

In this project the current handling capability of AlGaAs/GaAs HBT's is investigated. The idea is to use the HBT as a high- power and high-speed device. Multi-finger emitter and emitter ballasting resistor are used in the design of the HBT.

Research goals for the direct and resonant tunneling diode project

There are a lot of interests on both the direct tunneling and resonant tunneling diodes in recent years. Although there have been a lot of theoretical work done on the I–V characteristics on these kind of diodes, there seem to be a lack of agreement between experimental and theoretical results. One of the obvious shortcomings of those theoretical models is the non-inclusion of the proper band structure of the barrier material. In this project we used a $k \cdot p$ band model to calculate the complex wave-vectors of the tunneling electrons in the calculation of the I–V characteristics of these types of diodes. Another important point in the calculation is the inclusion of semiconductor band-bending. Since thin insulating barriers make-up part of the active device, band-bending in the semiconductor cannot be ignored. These ideas are tested in the model calculation and I–V characteristics so obtained are compared with the experimentally measured results.

B. Significant results of the past year

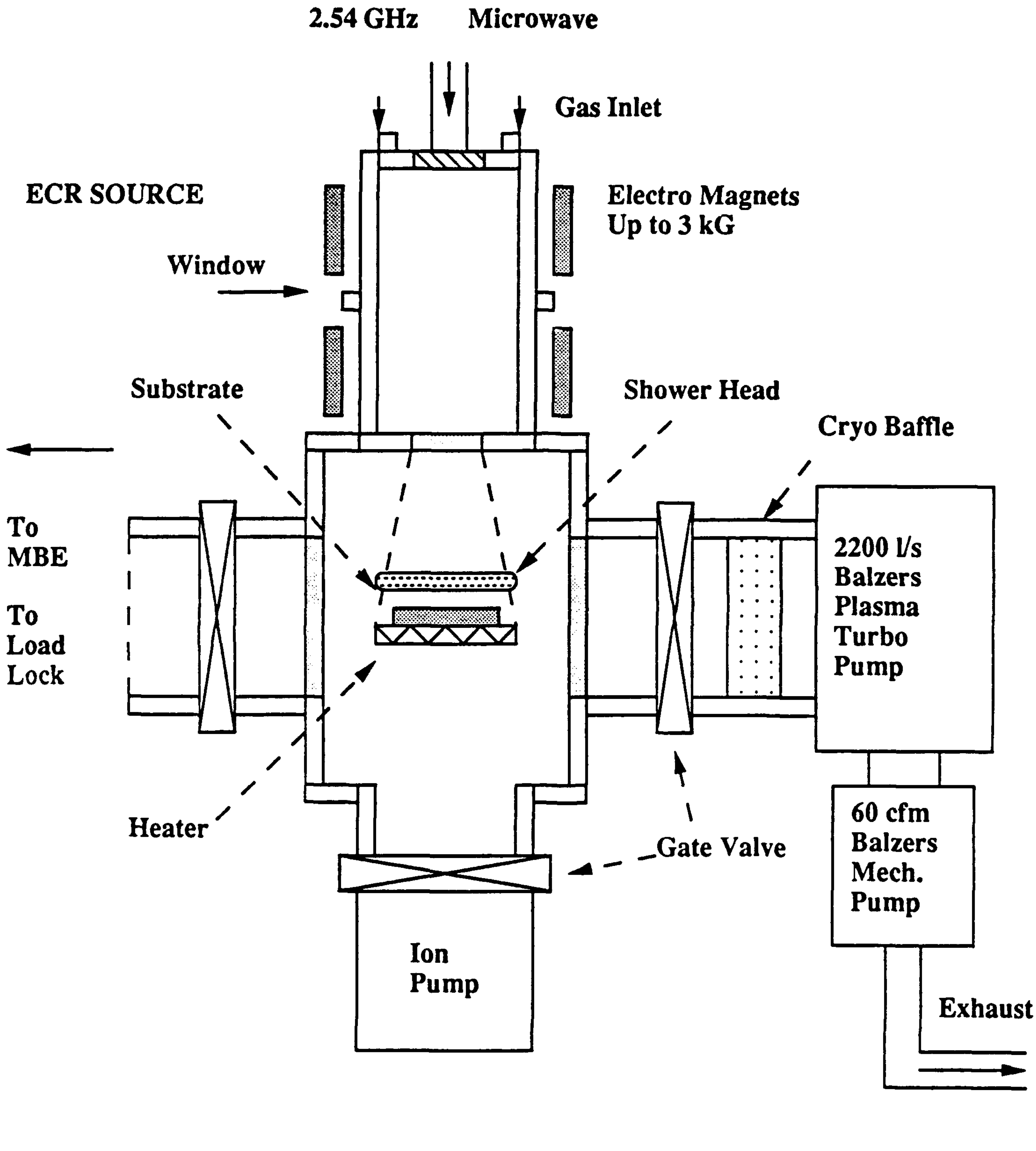
Results of the MISFET project

We have shown that surface Fermi level pinning is not an intrinsic property of compound semiconductor grown in ultra-high vacuum. A much reduced surface electric field was found in the GaAs surface when capped with a 20 Å Ge layer compared to an uncapped GaAs surface. This shows that the surface Fermi level of GaAs can be moved within the band-gap of the semiconductor by the use of an appropriate cap layer. This behavior indicates the presence of an unpinned surface. Similar results was obtained with a Si capped GaAs surface. A metal-oxide-semiconductor junction was fabricated with SiO_2 as the dielectric. High frequency capacitance-voltage curve shows that the surface electric field can be modulated by an externally applied voltage. Consistent with the results for Ge capped GaAs surface, Si capped GaAs surface is also shown to be unpinned.

The SiO_2 used in the MOS diode was deposited ex-situ in the remote-plasma chemical vapor deposition chamber using silane, oxygen, and helium. High quality SiO_2 is routinely obtained. For a 1000 Å thick oxide, a break-down field of larger than 3 MV/cm and a leakage current at 30 V bias of 6 nA/ cm^2 is obtained. The interface state density of the GaAs sample capped with Si is measured to be 6×10^{11} /eV/cm^2 around mid-gap by high frequency C-V measurements. This seemingly high interface state density is caused by the uncontrollable oxidation of the surface when the sample is being transferred from the growth chamber to the deposition chamber.

The deposition of ex-situ oxide, as we were forced into doing in those preliminary experiments, is not a good way of obtaining MOS diode with low interface state density. We believe that in-situ oxide deposition is the proper method, the setup of which was under construction. The in-situ oxide deposition system which includes an electron-cyclotron resonance (ECR) plasma source in our laboratory is now complete. Research in this area will start around mid-October, 1990. A figure of the ECR and CVD chamber is included in this report.

UHV-ECR CVD CHAMBER



Results of the Ge/GaAs HBT project

Initially for our investigations into the GaAs-Ge heterojunction system we concentrated on the individual junctions and tried to improve the quality of both the Ge/GaAs and GaAs/Ge junctions. Our initial results for epitaxial Ge grown on GaAs were quite encouraging. However, the polar on non-polar GaAs/Ge heterojunction presented more of a challenge. In this case, we had to worry about antiphase domain formation as well as cross doping across the heterointerface during the growth of GaAs which requires a relatively higher growth temperatures.

Following the lead of GaAs/Si researchers we investigated the role of vicinality of the (100) surface on antiphase domain formation. GaAs grown on nominally (100) Ge surfaces exhibited antiphase disorder which disappeared after roughly 500 Å of growth. TEM investigations confirmed that the antiphase domains propagated into the film along <111> planes and self-annihilated upon intersection leaving the final material single domain. When the experiments were repeated on (100) surfaces intentionally misoriented 4° towards [011], no significant evidence of antiphase disorder could be detected during growth or by TEM. Thus, the antiphase disorder problem can be avoided by using a misoriented (100) substrate.

The elimination of antiphase disorder through the introduction of a stepped surface has serious implications towards the role of steps in the growth of GaAs on Ge. To further investigate this, we grew layers which were initiated with a Ga prelayer as opposed to the As prelayer. We observed similar behavior in the antiphase domains except that in the nominally (100) case, the GaAs domain which remained after self annihilation was the opposite of the substrate orientation. This clue allowed us to propose a growth model of GaAs on Ge growth which is as follows. Of the two types of single steps available on the initial Ge surface, each must energetically favor either As or Ga. Thus when an unfavorable prelayer species is deposited at a step, the unfavorable species is exchanged with the opposite adatom upon growth initiation. This exchange propagates along the terrace length until the next monolayer is deposited or until the end of the terrace is reached and the lattice is in registry. For nominally straight substrates, the terrace lengths are too long to enable the lattice to correct itself before the next monolayer deposition

so the antiphase domain is "frozen in." In the vicinal case, the roughly 40 Å terrace lengths are sufficiently short for the lattice to become in registry. The final orientation of the GaAs domain in each of the four experiments undertaken allowed us to determine experimentally that the Ga-Ga bond is energetically favorable to the As-As one and we can therefore predict that the antiphase boundaries propagate along the <111>A Ga planes.

Following the successful growth of Ge/GaAs heterojunction, we have undertaken a systematic investigation of the electronic properties of Ge/(Al)GaAs heterojunction. First, we have studied the temperature dependent current-voltage characteristics of p- Ge/N-GaAs heterojunction diodes. At room temperature, unity ideality factor has been demonstrated over almost six decades of current suggesting an almost unhindered injection of electrons from N-GaAs into p-Ge. Later we have extended this study to current-voltage and capacitance-voltage characterization of Ge/(Al)GaAs junctions. Both structures exhibited nealy ideal room temperature current transport. From our capacitance-voltage and temperature dependent current-voltage measurements we deduced band discontinuity values which are in good agreement with the available data for Ge/GaAs and Ge/AlGaAs junctions. The nearly ideal reverse breakdown characteristics of Ge/GaAs and forward characteristics of Ge/AlGaAs junctions suggest Ge as an alternative to GaAs base in AlGaAs/GaAs HBT's to improve present device performances. We have demonstrated such a HBT (AlGaAs/Ge/GaAs) for the first time. The device exhibited a common-emitter current gain as high as 300. Measurements at low current levels and nearly ideal diode characteristics indicate low surface recombination current.

To study the impact of using Ge as the base on the performance of HBT's we have investigated low resistance contact formation on Ge and the influence of the contact resistance on the high-frequency response. Extremely low-resistance nonalloyed ohmic contacts have been formed on p-type Ge grown on GaAs. Using evaporated Ti/Al metalization specific contact resistances well below $1 \times 10^{-8}\Omega cm^2$ were achieved for heavily doped Ge ($p> 10^{19}cm^{-3}$.

One major obstacle towards the realization of Ge/GaAs HBT's is cross diffusion at the Ge/GaAs heterojunction. We have demonstrated that such a cross diffusion can be eliminated

by using an additional 10Å of pseudomorphic Si at the interface. We compared electrical characteristics, before and after annealing, of p-Ge/N-GaAs diodes with or without such Si diffusion barriers. Both types of diodes exhibited nearly ideal charactersitics prior to annealing. Diodes with no barriers showed significant degradation after aneealing at 640 °C. Diodes incorporating the Si interlayer retained excellent electrical performance after a 20 min anneal at temperatures as high as 720 °C.

Results of the power HBT project

Current handling capabilities of 400-800 mA/mm per emitter periphery at different case temperatures have been successfully demonstrated using a low-doped GaAs layer as an emitter ballasting resistor to obtain uniform current distribution over individual emitter fingers. A current gain at a collector current of 500 mA was realized at room temperature for three elementary devices bonded in parallel and each device is comprised of ten ($5\times25\mu m^2$) emitter fingers. Temperature dependence of the current gain at high current levels has been investigated concluding that high thermal resistance of GaAs limits the current handling capability of HBT's.

Results of the direct and resonant tunneling diode project

Both the direct and resonant tunneling diodes are investigated in this project. The heterojunction used is InGaAs/InAlAs lattice matched to InP. In order to explain the experimentally observed I–V characteristics we found that it is important to include both the semiconductor band–bending and the complex band structure of the barrier material. Since the current is so sensitive to the barrier thickness, the latter is measured accurately by the transmission electron microscope. The calculated I–V characteristics compared favorably with those measured for both diodes. This demonstrates not only the importance of using an accurate band structure in calculating the I–V characteristics of tunneling diodes but also the impor.ance of band–bending in devices with thin insulating layers. Since no non–elastic scattering event is included in the calculation, the closeness between the experimental and theoretical results also suggests that inelastic scattering during tunneling is not an important factor in determining the tunneling current.

C. Plans for next year's research

Future plans for the MISFET project

We have already demonstrated that GaAs surfaces can be prevented from pinning with the use of an appropriate Ge or Si cap layers, and we have evidence to suggest that this is not restricted to GaAs surface alone. With the possibility of an unpinned surface at hand, the next goal is to obtain MISFET's on compound semiconductors. In our work on Si capped GaAs MOS diode, the oxide was deposited ex- situ. This causes an uncontrollable oxidation on the surface which gave rise to the observed high interface state density. To circumvent this we have incorporated an electron–cyclotron resonance source in a chemical vapor deposition chamber which is connected to the growth chamber through a vacuum transfer tube. This allows us to do in–situ oxide deposition without breaking the vacuum. This we believe, will give us the capability of growing MISFET structures with very low interface state density and excellent bulk oxide properties. Our future plans on this project will be the study of the growth of MISFET structures with in–situ oxide deposition.

Future plans for Ge/GaAs HBT project

As our future plans, we will further investigate the Ge/GaAs system. With our knowledge on the growth mechanism, we are certain that we can improve the results we have already demonstrated. High frequency characterization of the HBT's will be considered. We will also study novel device structures combining the unique properties of Ge and (Al)GaAs material system. The investigation of Si diffusion barrier will be extended to the effect of such a thin layer of Si to the band alignment in Ge/GaAs junctions.

D. List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

1. M.S. Ünlü, S. Strite, S.N. Mohammad, K. Adomi, T. Won and H. Morkoç, "Characteristics of p-Ge/n-GaAs Heterojunctions Grown by Molecular Beam Epitaxy," *Electronic Lett.*, 24(20) , pp. 1359-1360, (1989).

2. M.S. Ünlü, S. Strite, G.B. Gao, K. Adomi and H. Morkoç, "Electrical Characteristics of p^+-Ge/(N-GaAs and N-AlGaAs) Junctions and Their Applications to Ge Base Transistors," *Appl. Phys. Lett.*, **56**,pp. 842-844, (1990).

3. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao and H. Morkoç, "AlGaAs/Ge/GaAs Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy," *IEEE Electron. Dev. Lett.*, 11, pp. 233-235, (1990).

4. M.S. Ünlü, S. Strite, K. Adomi, G.B. Gao and H. Morkoç, "Extremely Low-Resistance Non-alloyed Ohmic Contacts on Molecular Beam Epitaxially Grown p-type Ge," *Electronic Letts.*, **26(2)**, pp. 89-91, (1990).

5. S. Strite, M.S. Ünlü, K. Adomi and H. Morkoç, "Si as a Diffusion Barrier for Ge/GaAs Heterojunctions", *Appl. Phys. Lett.*, **56**, pp. 1673-1675, (1990).

6. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao, A. Agarwal, A. Rockett, H. Morkoç, D. Li, Y. Nakamura and N. Otsuka"GaAs/Ge/GaAs Heterostructures by Molecular Beam Epitaxy", Submitted to *J.V.S.T.*, pending.

7. M.S. Ünlü, G.B. Gao, T. Won, S.V. Iyer, J. Chen, and H. Morkoç, "500 mA AlGaAs/GaAs Power Heterojunction Bipolar Transistor," *Electron. Lett.*, 25, pp. 1447-1449,(1989).

8. S.Strite, D. Biswas, K. Adomi, H. Morkoç, "Sublattive orientation of GaAs on Ge", *J. Appl. Phys.* **67**, 1609(1990).

9. K. Adomi, S. Strite, H. Morkoç, "Antiphase–domain free GaAs grown on pseudomorphic Si(100) surfaces by molecular beam epitaxy", *Appl. Phys. Lett.* **56**, 469(1990).

10. S. Strite, D. Biswas, N. S. Kumar, M. Fradkin, H. Morkoç, "Antiphase domain–free growth of GaAs on Ge in GaAs/Ge/GaAs heterosturctures", *Appl. Phys. Lett.* **56**, 244(1990).

11. D. Mui, M. Patil, J. Chen, S. Agarwala, N. S. Kumar and H. Morkocç, "Modeling of the I-V characteristics of single and double barrier tunneling diodes using a $k \cdot p$ band model", *Solid State Elect.* , **32**, 1025(1989).

12. D. S. L. Mui, A. Salvador, S. strite, and H. Morkoç, "Effect of thin Ge layer on the surface depletion in GaAs", *Appl. Phys. Lett.* **57**, 572(1990).

2. Non–Refereed Publications and Published Technical Reports

3. Presentations

a. Invited

1. "Strained layer FETs, Lasers, and phototransistors in the InGaAs/GaAs/AlGaAs heterostructure systems", NATO Advanced Research Workshop on Condensed Systems of Low Dimensionality, Turkey, 1990.

2. "Strained layer FETs, Lasers, and phototransistors in the InGaAs/GaAs/AlGaAs heterostructure systems", 1990 Seoul International Symposium on the Physics of Semiconductors and Applications, Korea, 1990.

b. Contributed

1. S. Strite, K. Adomi, H. Morkoç, "Growth of antiphase domain free GaAs on epitaxial Ge by molecular beam epitaxy", Physics and Chemistry of Semiconductor Interfaces (PCSI-17), Clearwater Beach, FL, 1990.

2. S. Strite, M. S. Ünlü, K. Adomi, A. Rockett, H. Morkoç, "Si as a diffusion barrier for Ge/GaAs heterojuncions grown by molecular beam epitaxy", American Physical Society March Meeting, Anaheim, Ca, 1990.

4. Books

1. H. Morkoç, H. Ünlü, G. Ji, "Principles and Technology of Modulation Doped FETs", John Wiley and sons.
2. A book chapter to appear in "Processes in the Fabrication of GaAs Devices and Circuits", Ed. B. L. Sharma, "MBE Growth of GaAs and other Compound Semiconductors with Applications to Devices", by K. Adomi, J. I. Chyi, S. F. Fang, T. C. Shen, S. Strite, and H. Morkoç.

E. LIST OF HONORS/AWARDS

Name of Person Receiving Award	Recipient's Institution	Name, Sponsor and Purpose of Award
D. Mui	U. of Illinois	IBM fellowship
S. Strite	U. of Illinois	NSF and ASOFR fellowships

Enclosure (3)

H. SUMMARY OF FY90
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/PARTICIPANTS
(Number Only)

		ONR		non ONR
		This Project	Other ONR	
a.	Number of Papers Submitted to Referred Journal but not yet published:	1	4	
b.	Number of Papers Published in Refereed Journals:	11	2	
c.	Number of Books or Chapters Submitted but not yet Published:	2	2	
d.	Number of Books or Chapters Published:	0	0	
e.	Number of Printed Technical Reports & Non-Referred Papers:	0	2	
f.	Number of Patents Filed:	0	0	
g.	Number of Patents Granted:	0	0	
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	2	1	
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	2	2	
j.	Honors/Awards/Prizes for Contract/Grant Employees: (selected list attached)	3	1	
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grant:	4	9	
	Grad Students: TOTAL	4	9	
	Female	0	1	
	Minority	0	0	
	Post Doc: TOTAL	0	1	
	Female	0	0	
	Minority	0	0	
l.	Number of Female or Minority PIs or CO-PIs			
	New Female	0	0	
	Continuing Female	0	0	
	New Minority	0	0	
	Continuing Minority	0	0	

Enclosure (4)

337. S.L. Zhang, M.V. Klein, J. Klem and H. Morkoç, "Raman Scattering from Confined LO Phonons and Dispersion Relation in GaAs/AlGaAs Superlattices," *Phys. Lett. A*, **131**, pp. 69-72, (1988).

338. G. Ji, W. Dobbelaere, D. Huang and H. Morkoç, "Optical Transitions Involving Unconfined Energy States in InGaAs/GaAs Multiple Quantum Wells," *Phys. Rev. B*, **39**, pp. 3216-3222, (1989).

339. L.M. Smith, J.S. Preston, J.P. Wolfe, D.R. Wake, J. Klem, T. Henderson and H. Morkoç, "Phonon Wind Driven Transport of Photoexcited Carriers in a Semiconductor Quantum Well," *Phys. Rev. B.*, **39**, pp. 862-870, (1989).

340. T.Won, S. Agarwala, C.K. Peng and H. Morkoç, "Self Aligned $In_{0.52}Al_{0.48}As$/ $In_{0.53}Ga_{0.47}As$ Heterojunction Bipolar Transistors with Graded Interfaces on Semi Insulating InP Grown by Molecular Beam Epitaxy," *IEEE Electron. Dev. Lett.*, **EDL-10(3)** , pp. 138-140, (1989).

341. R.D. Groeber, H.D. Drew, J.I. Chyi, S. Kalem and H. Morkoç, "Infrared Photoluminescence of InAs Epilayers Grown on GaAs and Si Substrates," *J. Appl. Phys.*, **65**, pp. 4079-4081, (1989).

342. K.T. Tsen, O.F. Sankey, G. Halama, S.C.Y. Tsen and H. Morkoç, "Transport of Photoexcited Electron Hole Plasma in GaAs Quantum Wells," *Phys. Rev. B, Rapid Commun.*, **39**, pp. 6276, (1989).

343. F. Xiong, T.A. Tombrello, H. Eang, T.R. Chen, H. Morkoç and A. Yariv, "High Efficiency Single Quantum Well RIN-SCH Lasers Fabricated with MeV Oxygen Implantion," *Appl. Phys. Lett.*, **54**, pp. 730-732, (1989).

344. C. Kiely, J.I. Chyi, A. Rockett and H. Morkoç, "On the Microstructure and Interfacial Structure of InSb Layers Grown on GaAs (100) by Molecular Beam Epitaxy," *Philosophical Magazine*, **60(3)** , pp. 321-337, (1989).

345. M.W. Peterson, J.A. Turner, C.A. Parsons, A.J. Nozik, D.J. Arent, C. Van Hoof, G. Borghs, R. Houdré and H. Morkoç, "Miniband Dispersion in GaAs/$Al_xGa_{1-x}As$ Superlattices with Wide Wells and Very Thin Barrier Layers," *Appl. Phys. Lett.*, **53(26)** , pp. 2666-2668, (1989).

346. D. Huang, D. Mui and H. Morkoç, "Interference Effects Probed by Photoreflectance Spectroscopy," *J. Appl. Phys.*, **66**, pp. 358-361, (1989).

347. M.E. Hoenk, H.Z. Chen, A. Yariv, H. Morkoç and K.J. Vahala, "Cathofoluminescence Measurement of an Orientation Dependent Aluminum Concentration in $Al_xGa_{1-x}As$ Epilayers Grown by Molecular Beam Epitaxy on a Nonplanar Substrate," *Appl. Phys. Lett.*, 54(14) , pp. 1347-1349, (1989).

348. V.V. Gridin, R. Beserman and H. Morkoç, "Correspondence Between the Dependence of Frequencies and Intensities of GaAs and AlAs Longitudinal Optical Modes on the Photon Energy in a Thin Layer GaAs/AlAs Superlattice," *Phys. Rev. B*, **39**, pp. 1703, (1989).

349. I.Sela, R. Beserman and H. Morkoç, "Resonance Raman Scattering Induced Interface Roughness in a Short Period GaAs/AlGaAs Superlattice," *Phys. Rev. B*, **39**, pp. 3254, (1989).

350. S. Agarwala, T. Won and H. Morkoç, "AlGaAs/GaAs Single Heterojunction Bipolar Transistors Grown on InP by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, **54(12)** , pp. 1151-1153, (1989).

351. M.B. Patil, S.N. Mohammad and H. Morkoç, "Modeling of Field Effect Transistors with Laterally Graded Doping," *Solid State Electronics,* **32(9)** , pp. 791- 795, (1989).

352. S.N. Mohammad, M.B. Patil and H. Morkoç, "Heavy Doping for Improved Short Channel Operation of GaAs MESFETs," *Electronic Lett.,* **25**, pp. 331-332, (1989).

353. J.I. Chyi, D. Biswas, S.V. Iyer, N.S. Kumar, H. Morkoç, R. Bean, K. Zanio, H.Y. Lee and H. Chen, "Molecular Beam Epitaxial Growth and Characterization on InSb on Si," *Appl Phys. Lett.,* **54**, pp. 1016-1018, (1989).

354. H.J. Ou, S.C.Y. Tsen, K.T. Tsen, J.M. Cowley, J.I. Chyi, A. Salvador and H. Morkoç, "Determination of the Local Al Concentration in $Al_xGa_{1-x}As$/GaAs Quantum Well Structures Using (200) Diffraction Intensity Obtained with a 10Å Electron Beam," *Appl. Phys. Lett.,* **54**, pp. 1454, (1989).

355. T.Won, S. Iyer, S. Agarwala and H. Morkoç, "Collector Offset Voltage of Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy," *IEEE Electron. Dev. Lett.,* **EDL-10(6)** , pp. 274-276, (1989).

356. G.B. Gao, M.Z. Wang, X. Gui and H. Morkoç, "Thermal Design Studies of High Power Heterojunction Bipolar Transistors," *IEEE Trans. Electron. Dev.,* **ED-36(5)** , pp. 854-863, (1989).

357. P.W. Yu, C.K. Peng and H. Morkoç, "Photoluminescence from Carriers Confined at a $Ga_xIn_{1-x}As$/InP Single Heterojunction Interface," *Appl. Phys. Lett.,* **54(16)** , pp. 1546-1548, (1989).

358. J.I. Chyi, J. Chen, N.S. Kumar, C. Kiely, C.K. Peng, A. Rockett and H. Morkoç, "Low Resistance Nonalloyed Ohmic Contacts on p-Type GaAs Using GaSb/GaAs Strained Layer Superlattices," *Appl. Phys. Lett.,* **55(6)** , pp. 570-571, (1989).

359. J. Chen, G.B. Gao, D. Huang, J.I. Chyi, M.S. Ünlü and H. Morkoç, "Photo Emission from Avalanche Breakdown in the Collector Junction of GaAs/AlGaAs Heterojunction Bipolar Transistors," *Appl. Phys. Lett.,* **55**, pp. 374-376, (1989).

360. D.S.L. Mui, M.B. Patil and H. Morkoç, "Calculation of the Electron Wave Function in a Graded Channel Double Heterojunction Modulation Doped Field Effect Transistor," *Appl. Phys. Lett.,* **55(12)** , pp. 1223-1225, (1989).

361. S.N. Kumar, J.I. Chyi, C.K. Peng and H. Morkoç, "A GaAs Metal Semiconductor Field Effect Transistor with Extremely Low Resistance Non-Alloyed Ohmic Contacts Using an InAs/GaAs Superlattice," *Appl. Phys. Lett.,* **55**, pp. 775-776, (1989).

362. J. Chen, G.B. Gao, J.I. Chyi and H. Morkoç, "Breakdown Behavior of GaAs/ AlGaAs HBTs," *IEEE Trans. Electron. Dev.,* **ED-36(10)** , pp. 2165-2172, (1989).

363. M.S. Ünlü, S. Strite, S.N. Mohammad, K. Adomi, T. Won and H. Morkoç, "Characteristics of p-Ge/n-GaAs Heterojunctions Grown by Molecular Beam Epitaxy," *Electronic Lett.,* **24(20)** , pp. 1359-1360, (1989).

364. M.S. Ünlü, G.B. Gao, T. Won, S.V. Iyer, J. Chen and H. Morkoç, "500 mA AlGaAs/GaAs Power Heterojunction Bipolar Transistor," *Electronic Lett.* **25(21)** , pp. 1447-1449, (1989).

365. U.K. Reddy, G. Ji, T. Henderson, D. Huang, R. Houdré, H. Morkoç and C.W. Litton, "Interband Transistions in InGaAs/GaAs Strained Layer Superlattices," *J. of Vac. Sci and Technol.,* **B7(5)** , pp. 1106-1110, (1989).

366. B. Kh. Bairamov, T. Gant, M. Delaney, Y.E. Kitaev, M.V. Klein, D. Levi, H. Morkoç and R.A. Everestov, "A Theoretical and Experimental Investigation of Raman Scattering in the Size-quantizing Heterostructure Superlattices $(GaAs)_m$ $(AlAs)_n$," *Sov. Phys. JETP,* **68(6)** , pp. 1271- 1276, (1989).

367. D. Mui, M. Patil, J. Chen, N.S. Kumar and H. Morkoç, "Modeling of the I-V Characteristics of Single and Double Tunneling Diodes Using a $k \cdot p$ Band Model," *Solid State Electronics,* **32(11)**, pp. 1025-1031, (1989).

368. S.N. Mohammad, M.B. Patil, J.J. Chen, M.S. Ünlü, G.B. Gao and H. Morkoç, "Analytical Model for I-V Characteristics of Ion Implanted MESFETs," *IEEE Trans. Electron. Dev.,* **ED-37**, pp. 11-20, (1990).

369. S.N. Mohammad, M.B. Patil, J.J. Chen, M.S. Ünlü, and H. Morkoç, "Analytical Model for I-V Characteristics of JFETs with Heavily Doped Channels" *Solid State Electronics,* **33(1)**, pp. 53-64, (1990).

370. M.B. Patil and H. Morkoç, "Self-Consistent Calculation of Electron Density in a Two-Channel Modulation Doped Structure," *Solid State Electronics,* **33(1)**, pp. 99-104, (1990).

371. K. Adomi, S. Strite and H. Morkoç, "Antiphase Domain Free GaAs Grown on Pseudomorphic Si (100) Vicinal Surfaces by Molecular Beam Epitaxy," *Appl. Phys. Letts.,* **56(5)**, pp. 469-471, (1990).

372. S. Strite, D. Biswas, K. Adomi and H. Morkoç, "Study of Sublattice Orientation of GaAs on Ge," *J. Appl. Phys. Lett.,* **67(3)**, pp. 1609-1612, (1990).

373. M.S. Ünlü, S. Strite, K. Adomi, G.B. Gao and H. Morkoç, "Extremely Low-Resistance Non-alloyed Ohmic Contacts on Molecular Beam Epitaxially Grown p-type Ge," *Electronic Letts.,* **26(2)**, pp. 89-91, (1990).

374. H.J. Ou, J.M. Cowley, J.I. Chyi, A. Salvodor and H. Morkoç, "Microanalysis on the (200) Diffraction Intensity to Determine the Al Concentration for AlGaAs/GaAs MQWS Structures," *J. Appl. Phys.,* **67(2)**, pp. 698- 704, (1990).

375. G. Ji, D. Huang, T. Henderson, C.K. Peng and H. Morkoç, "Analysis of Energy States in Modualtion Doped Multiquantum Well Heterostructures," *Solid State Electronics,* **2**, pp. 247-258, (1990).

376. G.B. Gao, D. Huang, J. Chyi, J. Chen and H. Morkoç, "Current Induced Breakdown in P-Type Collector AlGaAs/GaAs HBTs," *IEEE Trans. on Electron. Dev.,* **37(3)**, pp.807-810, (1990).

377. M.S. Ünlü, S. Strite, K. Adomi, G.B. Gao and H. Morkoç, "Extremely Low Resistance Nonalloyed Ohmic Contacts on Molecular Beam Epitaxially Grown P-Type Ge," *Electronic Letts.,* **26(2)**, pp, 89-90, (1990).

378. S. Strite, M.S. Ünlü, K. Adomi and H. Morkoç, "Si as a Diffusion Barrier for Ge/GaAs Heterojunctions", *Appl. Phys. Lett.,* **56(17)**, pp. 1673-1675, (1990).

379. S. Strite, D. Biswas, N.S. Kumar, M. Fradkin and H. Morkoç, "Antiphase Domain Free Growth of GaAs on Ge in GaAs/Ge/GaAs Heterostructures," Submitted to *Appl. Phys. Lett.,* **56(3)**, pp. 244-246, (1990).

380. S.N. Mohammad, J. Chen, J. Chyi and H. Morkoç, "Suppression of Emitter Size Effect on the I-V Characteristics of GaAs/AlGaAs Heterojunction Bipolar Transistors," *Appl. Phys. Lett.*, **56(10)**, pp. 937-939, (1990).

381. G.B. Gao, D.J. Roulston and H. Morkoç, "Design Study of AlGaAs/GaAs HBTs," *IEEE Trans. on Electron. Dev.*, **37(5)**, pp. 1199-1208, (1990).

382. M.S. Ünlü, S. Strite, G.B. Gao, K. Adomi and H. Morkoç, "Electrical Characteristics of p^+-Ge/(N-GaAs and N-AlGaAs) Junctions and Their Applications to Ge Base Transistors," *Appl. Phys. Lett.*, **56(9)**, pp. 842- 844, (1990).

383. I. Adesida, A. Ketterson, J. Laskar, S. Agarwala, T. Brock, J. Kolodzey and H. Morkoç, "0.2μm T-Gate InAlAs/InGaAs MODFET with F_T = 170 GHz," *Microelectronic Engineering*, **11**, pp. 69-72, (1990).

384. P. Roblin, S.C. Kang and H. Morkoç, "Analytic Solution of the Velocity-Saturated MOSFET/MODFET Wave Equation and Its Application to the Prediction of the Microwave Characteristics of MODFET's," *IEEE Trans. on Electron. Dev.*, **37(7)**, pp. 1608-1622, (1990).

385. K. Shum, Y. Takiguchi, J.M. Mohaidat, F. Liu, R.R. Alfano and H. Morkoç, "Picosecond Hole Dynamics of in GaAs Grown on Silicon," *Appl. Phys. Lett.*, **56(23)**, pp. 2328-2330, (1990).

386. A. Salvador, J. Reed, N.S. Kumar, M.S. Unlu and H. Morkoç, "Electroabsorption Studies on GaAs Asymmetric Coupled Quantum Wells," *Surface Science*, **228**, 188-191, (1990).

387. D.S.L. Mui, A. Salvador, S. Strite and H. Morkoç, "Effect of Thin Ge Layer on the Surface Depletion in GaAs," *Appl. Phys. Lett.*, **57(6)**, pp. 572-574, (1990).

388. D. Huang, J.I. Chyi and H. Morkoç, "Carrier Effects on the Excitonic Absorption in GaAs Quantum Well Structures: Phase-Space Filling," *Phys. Rev. B*, **42(8)**, 5147-5153, (1990).

389. M.S. Ünlü, K. Kishino, J.I. Chyi, L. Arsenault, J. Reed, S.N. Mohammad and H. Morkoç, "Resonant Cavity Enhanced AlGaAs/GaAs Heterojunction Phototransistors with an Intermediate InGaAs Layer in the Collector," *Appl. Phys. Letts.*, **57(8)**, 750-752, (1990).

390. H.J. Ou, J.C. Barry, J.M. Cowley and H. Morkoç, "Distributions of the Al Concentration in $Al_xGa_{1-x}As$ Layer of $Al_xGa_{1-x}As$ MQWS Structure," Submitted to *Appl. Phys. Lett*, pending.

391. L.E. Eng, T.R. Chen, S.Sanders, Y.H. Zhuang, B. Zhao, A. Yariv and H. Morkoç, "Sub Milliampere Threshold Current Pseudomorphic InGaAs/AlGaAs Buried Heterostructure Quantum Well Lasers Grown by Molecular Beam Epitaxy," Submitted to *Appl. Phys. Lett.*.

392. T.N. Krabach, A.L. Kotz, M.V. Klein, N.S. Kumar and H. Morkoç, "Brillouin Scattering Measurements of Elastic Constants of $Al_xGa_{1-x}As$," Submitted to *Phys. Rev. Lett.*.

393. G.B. Gao, D.J. Roulston and H. Morkoç, "Is Npn or Pnp the Better Choice for Millimeter Wave AlGaAs/GaAs HBTs?," Submitted to *Solid State Electronics*, in press.

394. K. Shum, K.S. Wong, H.S. Chao, R.R. Alfano, S.V. Iyer and H. Morkoç, "Picosecond Dynamics of Exciton Capture by Neutral Carbon Acceptors in GaAs Quantum Wells," Submitted to *Phys. Rev. B*, pending.

395. G.B. Gao, J.I. Chyi, J. Chen and H. Morkoç, "Emitter Region Delay Time of AlGaAs/GaAs Heterojunction Bipolar Transistors," Submitted to *Solid State Electronics*, in press.

396. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao and H. Morkoç, "AlGaAs/Ge/GaAs Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy," Submitted to *IEEE Electron. Dev. Lett.*, pending.

397. K.Shum, H.S. Chao, R.R. Alfano, S.V. Iyer and H. Morkoç, "Hydrogen-Molecule-Like Complex in Undoped GaAs Quantum Wells," Submitted to *Phys. Rev. Letts.*, pending.

398. K.T. Tsen, G. Halama, O.F. Sankey, S.C.Y. Tsen and H. Morkoç, "Time Resolved Raman Studies of the Photoexcited Electron Hole Plasma in InP," Submitted to *Phys. Rev. B Rapid Commun.*, in press.

399. E.D. Specht, G.E. Ice, C.J. Peters, C.J. Sparks, N. Lucas, H. Morkoç and X.M. Zhu, "X-Ray Diffraction Measurement of Interface Structure in GaAs/Si (001)," Submitted to *Phys. Rev. B*, pending.

400. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao, A. Agarwal, A. Rockett, H. Morkoç, D. Li, Y. Nakamura and N. Otsuka"GaAs/Ge/GaAs Heterostructures by Molecular Beam Epitaxy", Submitted to *J. Vac. Sci. and Tech.*, pending.

401. S.N. Mohammad and H. Morkoç, "Optically Controlled Current-Voltage Characteristics of Ion-Implanted MESFETs," Submitted to *Solid State Electron.*, in press.

402. G.B. Gao, M.S. Ünlü, and H. Morkoç, "Emitter Ballasting Resistor Design for, and Current Handling Capability of AlGaAs/GaAs Power Heterojunction Bipolar Transistors," Submitted to *IEEE Trans. on Electron Dev.*,, pending.

403. H. Morkoç, "MODFETs Reach New Heights with Cut- Off Frequencies over 400 GHz," Submitted to *IEEE Circ. and Dev. Magazine*, pending.

404. H. Morkoç and G.B. Gao, "Heterojunction Bipolar Transistors (HBTs) Crack the 200 GHz Barrier," Submitted to *IEEE Circ. and Dev.*, pending.

405. A. Salvador, J. Reed, M.S. Ünlü, T.C. Shen, L. Arsenault and H. Morkoç, "Electroabsorption in Strongly Coupled Asymmetric Quantum Wells," Submitted to *Appl. Phys. Letts.*, pending.

406. A. Salvador, K. Adomi, K. Kishino, M.S. Ünlü and H. Morkoç, "GaAs Multiple Quantum Well Reflector Modulators Grown on Si," Submitted to *Appl. Phys. Letts.*, pending.

407. J.I. Chyi, D. Mui, J. Chen and H. Morkoç, "Electrical Characteristics of InSb/GaAs Heterojunctions," Submitted to *Applied Phys. Letts.*, pending.

408. M.S. Ünlü, G.B. Gao, K. Adomi, J. Chen, G.X. Liu and H. Morkoç, "Double Layer Collector Power AlGaAs/GaAs Heterojunction Bipolar Transistors on Si," Submitted to *IEEE Electron Dev. Letts.*, pending.

409. M.S. Ünlü, K. Kishino, J.I. Chyi, L. Arsenault, J. Reed and H. Morkoç, "Wavelength Demultiplexing Heterojunction Phototransistor," Submitted to *Electronic Letts.*, pending.

410. K. Adomi, S. Strite, H. Morkoç, Y. Nakamura and N. Otsuka, "Characterization of the GaAs on Si Interface Using a Si Interlayer Grown on GaAs Substrates," Submitted to *J. Appl. Phys.*, pending.

411. S.N. Mohammad, J. Chen, J.I. Chyi and H. Morkoç, "The Effect of Base Doping Gradients on the Electrical Performance of AlGaAs/GaAs Heterojunction Bipolar Transistors," *Appl. Phys. Letts.*, in press.

412. R.K. Ahrenkiel, B.M. Keyes, T.C. Shen, J.I. Chyi and H. Morkoç, "Minority-Carrier Lifetime in Al_xGa_{1-x}as Grown by Molecular Beam Epitaxy," Submitted to *J. Appl. Phys.*, pending.

413. B. Mazhari, G.B. Gao and H. Morkoç, "Collector- Emitter Offset Voltage in Heterojunction Bipolar Transistors," Submitted to *Solid State Electronics*, pending.

414. J. Chen, G.B. Gao and H. Morkoç, "The Thermal Dependence of HBT High-Frequency Performance," submitted to *IEE Electronic Letters*, pending.

415. J.C. Costa, F. Williamson, T.J. Miller, K. Beyzavi, M.I. Nathan, D.S.L Mui, S. Strite and H. Morkoç, "Barrier Height Variation in Al/GaAs Schottky Diodes with a Thin Silicon Interfacial Layer," Submitted to *Appl. Phys. Lett.*, pending.

416. D.S.L. Mui, K.R. Evans, S.F. Fang and H. Morkoç, "Use of Methane in an Electron Cyclotron Resonance Source for Carbon Doping in GaAs Molecular Beam Epitaxy," Subimitted to *Appl. Phys. Lett.*, pending.

417.